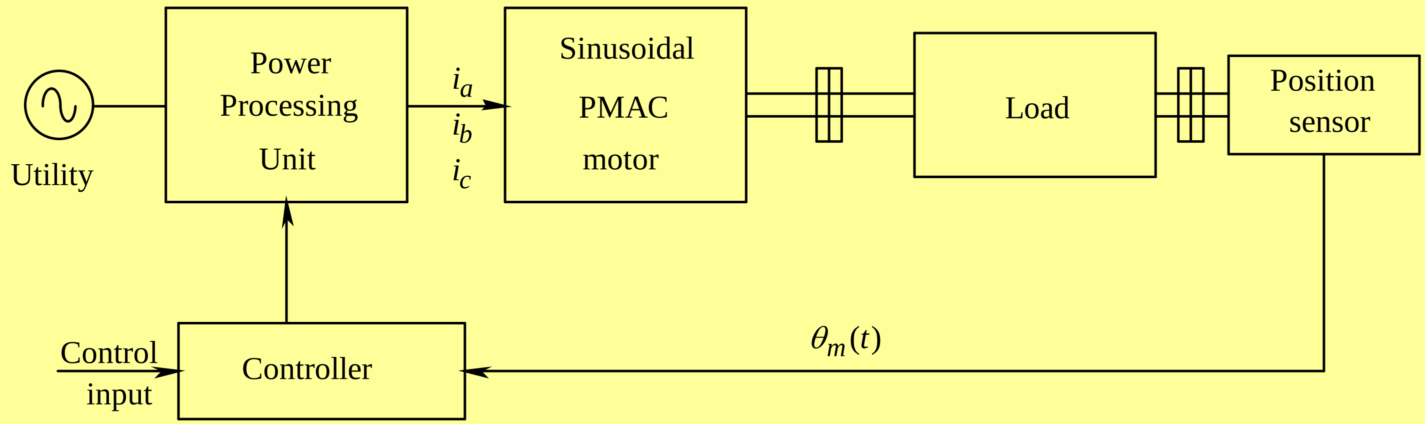
Sinusoidal Permanent Magnet AC (PMAC) Drives

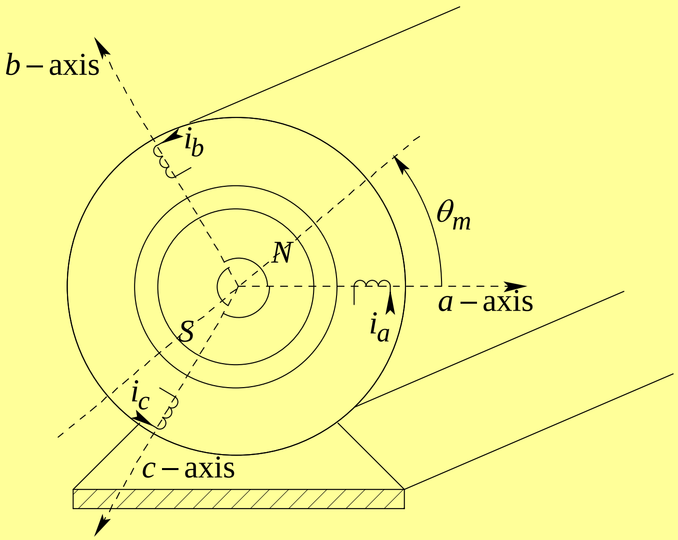
- Block Diagram
- Structure of Permanent-Magnet Synchronous Machines
- Principle of Operation
- Torque Calculation
- Similarity Between DC Motor and Brushless DC Motor
- Mechanical System
- Calculation of the Reference Current Values

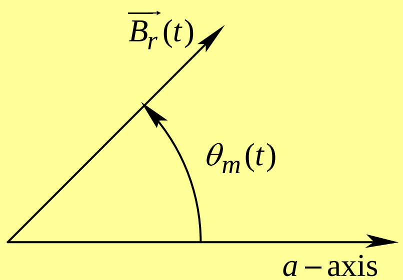
Permanent-Magnet AC (PMAC) Drives



- ☐ System level operation similar to DC machines but without brushes - sometimes called Brush-less DC Drives
- ☐ Motor essentially a synchronous machine whose field flux is provided by permanent magnets

Structure of Permanent-Magnet Synchronous Machines





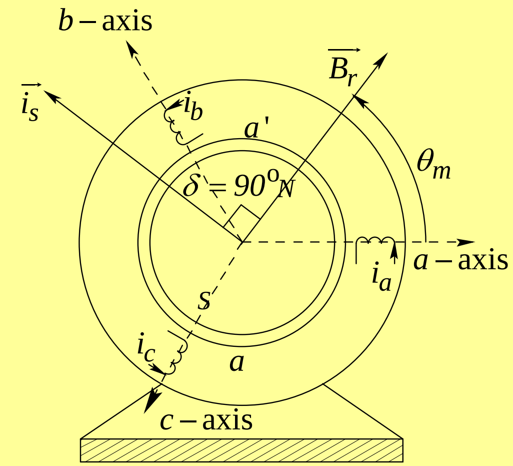
- ☐ Permanent Magnet rotor
- ☐ Sinusoidally distributed stator windings

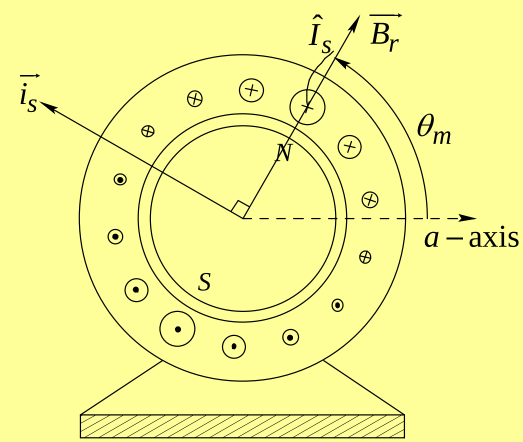
Principle of Operation

- Magnets shaped to produce sinusoidal flux density distribution

$$\overrightarrow{B_r}(t) = \hat{B}_r \angle \theta_m(t)$$

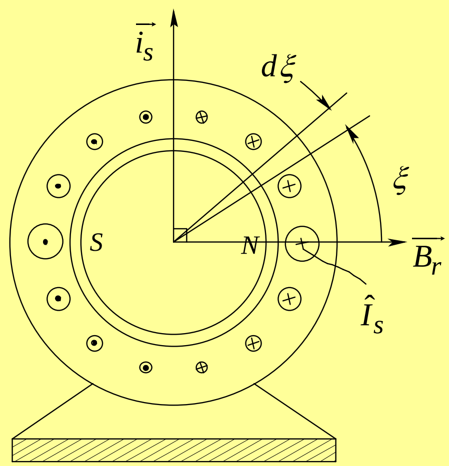
- Controlled stator currents
  - $\vec{i}_s(t)$ controlled by PPU (controlling $i_a(t)$, $i_b(t)$, and $i_c(t)$) such that
    $\vec{i}_s(t) = \hat{I}_s(t) \angle \theta_{i_s}(t)$, where
    $\theta_{i_s}(t) = \theta_m(t) + 90^0$
  - $\delta = 90^o$ maximizes torque/ampere
  - Stator current space vector is controlled so that it leads the peak rotor flux by 90 degrees





Torque Calculation

Using $f_{em} = Bli$



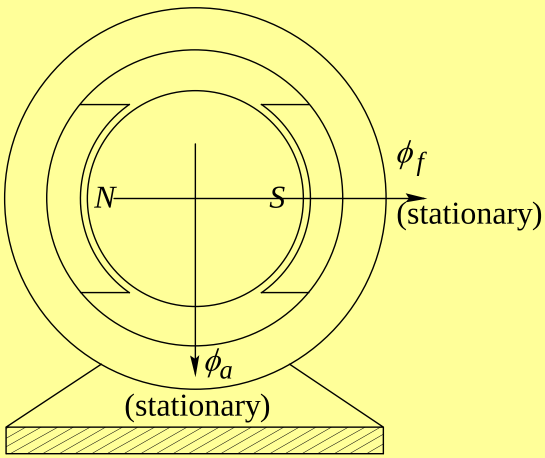
$$dT_{em}(\xi) = r \underbrace{\hat{B}_r \cos\xi}_{flux\,density\,at\,\xi} \cdot \underbrace{\ell}_{cond.length} \cdot \hat{I}_s \cdot \underbrace{\frac{N_s}{2}\cos\xi \cdot d\xi}_{diff\ no.of\ cond.at\,\xi}$$

$$T_{em} = 2 \times \int_{\xi=-\pi/2}^{\xi=\pi/2} dT_{em}(\xi) = 2\frac{N_s}{2} r\ell\hat{B}_r\hat{I}_s \int_{-\pi/2}^{\pi/2} \cos^2\xi \cdot d\xi = \left[\pi\frac{N_s}{2} r\ell\hat{B}_r\right]\hat{I}_s$$

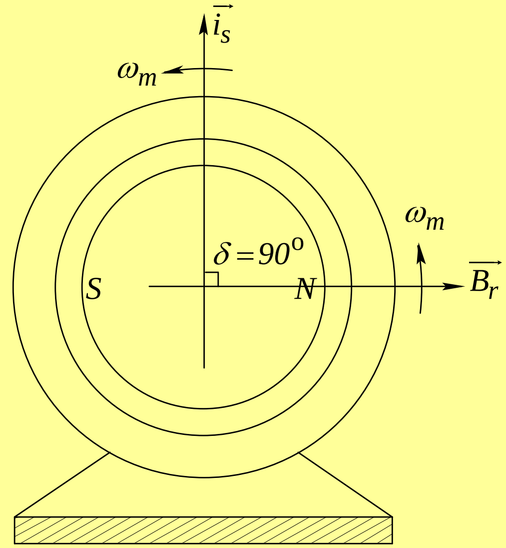
$$\Rightarrow T_{em} = k_T\,\hat{I}_s, \text{ where the machine torque constant, } k_T = \pi\frac{N_s}{2} r\,\ell\,\hat{B}_r$$

- ☐ Torque is proportional to $\hat{I}_s$ alone, just as in dc motors with constant field excitation. Hence the name Brush-Less DC

Similarity Between DC Motor and Brushless DC Motor



DC motor

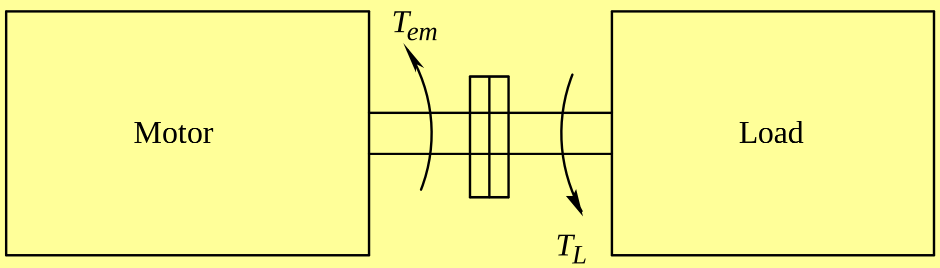


Brush-Less DC motor drive

- Stationary ϕ_f produced by stator windings
- ϕ_a produced by rotating rotor windings and is made stationary by commutator action

- $\vec{B_r}$ produced by rotor magnets and rotates with the rotor
- $\vec{i_s}$ produced by stator winding currents and is made to rotate at rotor speed by the action of the PPU

Mechanical System



$$\alpha_m = \frac{d\omega_m}{dt} = \frac{T_{em} - T_L}{J_{eq}}$$

$$\omega_m(t) = \omega_m(0) + \int_o^t \alpha_m(\tau) \cdot d\tau$$

$$\theta_m(t) = \theta_m(0) + \int_o^t \omega_m(\tau) \cdot d\tau$$

Calculation of the Reference Values: $i_a^*, \ i_b^*$ and i_c^*

- Reference values are generated by the controller based on desired torque output and rotor position
- Reference values tell the PPU what stator currents to deliver
- Starting with the desired torque and known rotor position, the desired stator currents are found as follows:

$$(T_{em}^*, \theta_m) \rightarrow (\vec{i}_s) \rightarrow (i_a^*, i_b^*, i_c^*)$$

$$\hat{I}_s^*(t) = \frac{T_{em}^*(t)}{k_T}$$

$$\theta_{i_s}^*(t) = \theta_m(t) + 90^0$$

$$\vec{i}_s^*(t) = \hat{I}_s^*(t) \angle \theta_{i_s}^*(t)$$

$$i_a^*(t) = \frac{2}{3} \text{Re}\left[\vec{i}_s^*(t)\right] = \frac{2}{3} \hat{I}_s^*(t) \cos \theta_{i_s}^*(t)$$

$$i_b^*(t) = \frac{2}{3} \text{Re}\left[\vec{i}_s^*(t) \angle -120^0\right] = \frac{2}{3} \hat{I}_s^*(t) \cos(\theta_{i_s}^*(t) - 120^0)$$

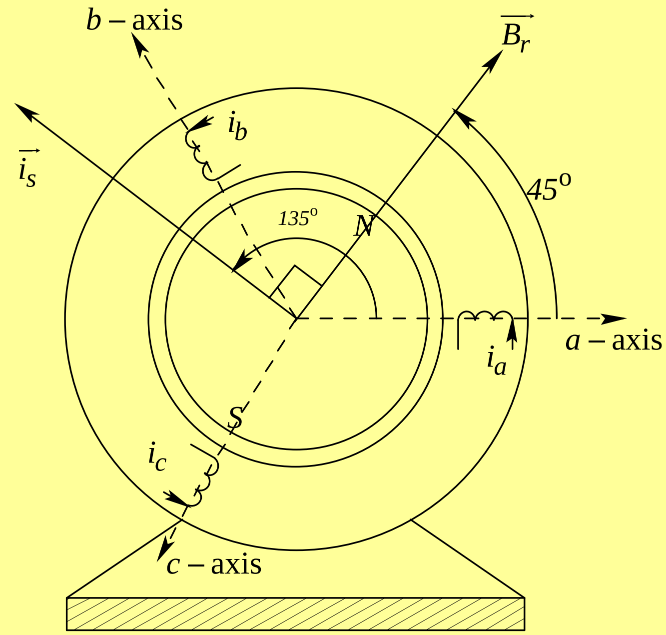
$$i_c^*(t) = \frac{2}{3} \text{Re}\left[\vec{i}_s^*(t) \angle -240^0\right] = \frac{2}{3} \hat{I}_s^*(t) \cos(\theta_{i_s}^*(t) - 240^0)$$

Example

k_T = 0.5 Nm/A

To produce a counter clockwise holding torque of 5 Nm at

$$\theta_m = 45°$$



$$\hat{I}_s = \frac{T_{em}}{k_T} = 10\ A$$

$$\theta_{i_s} = \theta_m + 90^0 = 135^0$$

$$\vec{i}_s = \hat{I}_s \angle \theta_{i_s} = 10 \angle 135^0$$

$$i_a = \frac{2}{3}\hat{I}_s \cos\theta_{i_s} = -4.71\ A \qquad i_b = \frac{2}{3}\hat{I}_s \cos(\theta_{i_s} - 120^0) = 6.44\ A$$

$$i_c = \frac{2}{3}\hat{I}_s \cos(\theta_{i_s} - 240^0) = -1.73\ A$$

Stator currents are dc in this example.

Summary

Sinusoidal Permanent Magnet AC Drives

- Block Diagram
- Structure of Permanent-Magnet Synchronous Machines
- Principle of Operation
- Torque Calculation
- Similarity Between DC Motor and Brushless DC Motor
- Mechanical System
- Calculation of the Reference Current Values